Site and Reach Assessment
North Fork Nooksack River at SR 542, MP 28.8 – 31.0

Work Order MT0100

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Summary

State Route 542 is located between an active alluvial fan and wide, braided section of the North Fork Nooksack River (NFNR). The river has created Warnick Bluff by eroding into the distal ends of the alluvial fan. There are three areas of immediate concern with the project reach, each designated as a “section”: Warnick Bluff; Warnick Bridge; and Canyon Creek alluvial fan. Habitat restoration being considered by Whatcom County and others potentially threatens the west approach to the Warnick Bridge.

Report findings:

- Warnick bluff has retreated during the last 60 years, but much faster during the last 10 years.
- Warnick Bluff has retreated due to a combination of toe erosion and slope failure.
- Warnick Bluff is currently unstable, and could retreat further without additional toe erosion; however, further toe erosion would accelerate this process.
- Construction of the Warnick Bridge significantly narrowed the North Fork Nooksack River during high flows.
- Pulses of sediment move through the portion of the river under Warnick Bridge.
- Canyon Creek and its alluvial fan influence the North Fork Nooksack by increasing sediment load, which results in a locally increased gradient.
- Confinement of Canyon Creek to a smaller portion of its alluvial fan may have resulted in increased sediment input, exacerbating the instability of the North Fork Nooksack farther downstream.
- The active channel migration zone of the North Fork Nooksack has fluctuated in both width and location during the last 70 years.

Report recommendations:

- Highway relocation to avoid bluff erosion and alluvial fan deposition is warranted.
- A phased approach is recommended, with initial road relocation and simultaneous long-range planning for a larger relocation project.
- The highway should be moved away from the eroding Warnick Bluff, initially to an unused WSDOT right-of-way.
- The west approach to Warnick Bridge should be protected from potential scour and deposition along the Canyon Creek alluvial fan.
- In 15 to 20 years, the highway should be moved between MP28.8 and MP 31.9, to a route along the north side of the valley.
- Along the future route, two new bridges would be built, one on the Nooksack, upstream from the Warnick Bridge, and one across Canyon Creek, at the apex of the alluvial fan.
1.0. Introduction

The project reach is located in Whatcom County, between river mile (RM) 52 and 55 on the North Fork Nooksack River (NFNR). Figure 1 shows the location and environs of the reach. The highway milepost ranges from 28.8 to 30.1. There are three areas of concern in this reach, Warnick Bluff, Warnick Bridge, and the Canyon Creek Alluvial Fan.

The Warnick Bluff section consists of locations where the NFNR is currently affecting or can potentially affect the highway due to erosion of the base of Warnick Bluff. The bluff extends from just west of the Warnick Bridge (at MP 30.9) to MP 28.8. The bluff is about 60 feet high. A portion of the highway had to be moved in 2007 to avoid being undermined by the river.

The Warnick Bridge section is located where the highway crosses the NFNR, at MP 30.1. The bridge is a steel truss bridge and was built in 1930. The piers supporting the bridge, and the east and west approaches, are affected by erosion. Several repairs have been made to the approaches, mainly installation of rip rap revetment. This has been done as recently as 2006, and there is already evidence of erosion.

The Canyon Creek alluvial fan is included this reach assessment because it indirectly affects erosion of the bridge abutments, because it has the potential to affect the highway immediately west of the Warnick Bridge, and because it may influence the rate of channel migration, affecting Warnick Bluff. Canyon Creek is partially confined in the fan reach due to an armored berm constructed in 1994. This has affected sediment transport to the NFNR. Whatcom County has developed plans to remove the berm and restore fish habitat and passage to the reach. Two different lengths of berm are being considered for removal. However, with the berm removed, there is a risk of the highway being affected by debris flows and large floods.

This reach of the NFNR has been previously recognized as a high risk area. Several recent reports indicate that the danger to the highway is high, and could be severe (GeoEngineers, 2001; Kerr Wood Leidel, 2003; Herrera Environmental, 2007). While the activity at Warnick Bluff has triggered the CED designation, all three sites warrant collective consideration.
Figure 1. Location Map, SR 542.
2.0. Methods

This study included literature and data review as well as field reconnaissance. We also conducted synthesis of relevant aerial photos, ground photos taken at the site, topographic maps, geology maps and reports, LIDAR data, fish distribution data, and hydrologic data. Sources of information include:

- Ground photos obtained by environmental staff during site visits in 2008.
- GIS coverages of 24K USGS topographic maps for this area.
- Existing literature and data, as listed in the “References” section of this report.
- Fish distribution information available from the Washington Lakes and Rivers Information System (WLRIS).
- Engineering records from WSDOT headquarters

Field reconnaissance was also conducted. To understand the nature of sediment transport, and river hydraulics, a longitudinal profile was surveyed using a self-leveling level, a surveyor’s tape, and stadia rod. The profile was surveyed using the water’s edge, in two places, centered on the Warnick Bridge, and at and upstream of Warnick Bluff. Pebble counts were taken at eight representative sites, using the random-walk method.

To understand potential mechanisms of mass wasting at the bluff, a spreadsheet-based bank stability analysis model (B-STEM) was employed. This model uses inputs from stream flow, bank material characteristics, and topography to calculate the Factor of Safety of streambanks.
3.0. Site Assessment

Each of the three sites (“sections”) is different from the other, but linked by proximity and geomorphic processes. Figure 2 shows site locations and key features with an aerial photograph base. Each site is discussed in the following sections.

3.1 Warnick Bluff

This site is located at MP 28.9 on SR542. The site is characterized by a 60-foot high bluff above the NFNR (Figure 3). While this assessment focuses on a specific spot along the bluff (where the highway is most threatened), the bluff is roughly consistent in height, slope, and aspect along its approximately 6,000 foot length. While there has been a bluff here since the topographic survey of the area (War Department, 1915), the bluff retreated in recent decades, with acceleration of retreat occurring in the last 10 years (Lummi Nation, personal communication to Roger Nichols, USFS, 2007). The bluff retreated approximately 90 feet between 1938 and 1994 (1.6 ft/yr), and about 54 feet between 1994 and 2005 (4.5 ft/yr) (Tim Hyatt, Nooksack Tribe biologist, personal communication to Roger Nichols, 2006). The bluff further retreated up to 15 feet in the fall of 2006 (primarily in one storm event).

The bluff appears to retreat by a two-phase process: by removal of the toe by the NFNR, followed by shear failure of the destabilized bluff slope. In addition, between periods of toe erosion, gravity-induced spalling of material from the face of the bluff results in talus slopes at the base of the bluff. At least 4 stratigraphic layers are present: a sandy topsoil, a debris flow unit (likely older Canyon Creek alluvial fan deposits), a mixed sand and gravel unit, and a thick unit with lenses of fine sand interspersed with gravel. Figure 3 shows the stratigraphic layers identified during this study. Springs were observed emerging at the contact of units 3 and 4. Hydrostatic pressure build-up at this interface may also contribute to bluff retreat, due to rotational or slab failure above the contact. Figure 4 shows a typical ground profile of the bluff.

The bluff retreated to within 5 feet of the highway in November of 2006, and emergency repair work was initiated. The highway was moved to the northeast, within the WSDOT right-of-way. A culvert drainage problem was fixed, and new culverts installed to carry roadside drainage out over the bluff. The water from the culverts drops 30 feet, hitting the debris at the toe of the bluff (see Figure 5).
Figure 2. SR542 section location map.
Figure 3. Warnick Bluff stratigraphy.
1: sandy topsoil; 2: heterogeneous debris flow deposits (Canyon Creek Alluvial Fan); 3: Coarse sand and gravel; 4: fine sand and gravel of ancestral (?) NFNR; 5: recent talus deposits. Note 25-foot stadia rod for scale.
Figure 4. Warnick Bluff profile with key features, looking downstream.

Figure 5. Toe protection installed at Warnick Bluff in 2006.
A bank stabilization program was begun in 2007, as a cooperative effort between the U.S. Forest Service and the WSDOT. As a result, a series of structures were installed at the base of the recently eroded bluff in fall of 2006 (Figure 5). These structures are composed of bucked logs (without rootwads) that are held in place by 1-inch cables fixed to large boulders (>3.5 feet diameter). Approximately 600 feet of toe protection was installed. Further to the east, (about MP 30.4), another 600 feet of bluff is scheduled for protection with additional log and rock structures in 2008.

3.2 Warnick Bridge section

This section consists of the bridge that crosses the NFNR, and environs (Figure 6). The bridge site was chosen due to the relatively confined nature of the river at this point (see Figure 2). However, it is also the reason why the bridge has experienced scour around the concrete piers. The bridge is approximately 150 feet long and 32 feet wide. The piers are made of concrete, and are built at a bottom elevation of 709 feet elevation (above mean sea level). Figure 7 shows the bridge plan from 1930. Note that the ground elevation on the west is significantly lower than on the right. There is an embankment in place now, occupying the space between the original groundline and the highway. Based on the “high water” elevation shown in the original plan, the floodway at that elevation was reduced by nearly 50 percent, due to the approaches to the bridge (riprap has been placed around Pier 1, encroaching further than the original west approach).

Scour surveys show that the river bottom has been as low as 713 feet, though not next to the piers. Bridge inspection reports make reference to scour calculations predicting scour below the bottom of piers, but note that rip rap placed around piers “may help prevent local scour at the piers.” However, this protection is beginning to fail on both upstream and downstream sides of Pier 1, as the river is undercutting the rip rap. Figure 7 shows a photograph of the failing rip rap. Notably, debris avalanche landslides are occurring immediately upstream of the bridge, within the Church Mountain landslide (see Section 4.2, below); a landslide close to the bridge is shown in Figure 8.
Figure 6. Warnick Bridge looking upstream.
Note longitudinal bar in foreground.

Figure 7. Warnick Bridge plan.
Source: WSDOT engineering records.
Figure 8. Riprap sloughing on west approach to Warnick Bridge.
The gravel berm in the foreground is the upstream extension of the longitudinal bar shown in Figure 6.

Figure 9. Landslide in Church Mt. landslide deposits, above Warnick Bridge.
Facing downstream, the bridge in the background.
During the flood of 1995 on Canyon Creek, the fan deposits extended out in the NFNR floodplain upstream from the bridge. NFNR flow was diverted to the left bank, reactivating landslide deposits, and causing scour behind Pier 2. The bank upstream and downstream of Pier 2 was subsequently covered with new rip rap.

### 3.3 Canyon Creek Alluvial Fan

Canyon Creek joins the NFNR just above the Warnick Bridge. Canyon Creek drains a steep, 31 square mile watershed from the north and east. There are two major deep-seated landslides (discussed further in section 4.2), and numerous shallow-rapid landslide and scars within the Canyon Creek watershed. These all contribute to a very high sediment load. Most of the Glacier Springs subdivision is built on the alluvial fan (see Figure 2).

Two debris floods occurred, in 1989, and 1990. Major damage was sustained to the Glacier Springs subdivision; because of topography developed after the 1989 flood, the damage in 1990 was actually worse, even though discharge was somewhat smaller. In 1990, a rock-lined berm and several rock groins were installed by the Soil Conservation Service (now the NRCS). During the 1989 flood, flood water was observed flowing in the ditch adjacent to the north side of SR542 near the Warnick Bridge (GeoEngineers, 1992). Immediately after the flood, a bypass channel was cut 1200 feet long, near the apex, on the east side of the fan. The bypass channel has since been cut off from the stream by further stream incision; the bypass channel is now filling in with vegetation.

In 1994, a dike up to 35 feet high was constructed to protect public road rights of way and private lots in Glacier Springs. About 2,400 feet of the dike was built with rip rap on the channel side. The rock was sized to 4.9 feet to withstand an estimated 5000 cfs flood. The lower 450 feet of the dike was built without rip rap protection. Rock groins were installed in 5 locations, and bedrock was blasted in an effort to minimize deflection to the right side of the active floodplain. During 1995, a significant flood occurred, removing the unarmored section of the dike.

In 2003, Whatcom County had a study conducted on the causes of debris floods and the risks of them in the future. The study concluded that the debris floods were the result of dam break floods, related to deep-seated landslides upstream. The same year, Whatcom County received funds to buy out The Logs Resort, which occupied a significant portion of the lower active fan and high hazard zone.

There have been plans to restore or enhance fish habitat on Canyon Creek, in the alluvial fan section. The U.S. Forest Service has developed conceptual plans for restoration (USDA, 2005), that include moving the channel out of the bedrock notch, removing the dike completely, and providing roughness elements in the active channel, among other items. The Nooksack Tribe also developed plans for restoration. Whatcom County received a grant in 2006 to develop a comprehensive restoration strategy for the Canyon Creek alluvial fan. As part of that effort, a new assessment was made of the fan, by Herrera Consultants (Whatcom County, 2007); this report identified more recent channel changes and devised conceptual (30 percent) design for various elements of restoration.
Figure 10. Just below apex of Canyon Creek Alluvial Fan, March, 2008. Looking downstream. Note that the toe of the dike has been partially eroded.

Figure 11. Oblique aerial view of Canyon Creek Alluvial Fan, 2002. (Courtesy of Whatcom County)
4.0. Reach Assessment.

4.1 Watershed Conditions and Land Cover

Most of the ownership of the North Fork Nooksack watershed above Warnick Bluff is United States Forest Service (see Figure 12), although there are some state lands and private lands located mostly along the highway. Much of the watershed is wilderness; the remainder is timberlands that are actively logged, being owned either privately or by the Washington Department of Natural Resources. About 55 percent of the watershed is National Forest non-wilderness, 24 percent is National Forest wilderness area, about 8 percent is National Park, and about 13 percent is zoned for commercial forestry. The watershed has been subjected to heavy logging, small scale development of residential and commercial properties, stand-replacing fires, and floods and debris flows.

The Canyon Creek watershed is 31 square miles in area; its ownership is 87.4 percent Forest Service (Mt. Baker Snoqualmie National Forest); 2.4 percent Washington State Department of Natural Resources; and 11.2 percent private timberlands. Past disturbances include heavy logging, 200-300 year recurrence interval, stand-replacing fires, earth flows, debris avalanches, and major floods. There is an extensive road network, allowing access to most of the watershed.

Figure 12. Whatcom County zoning in NFNR watershed, above project reach.
4.2 Geology and Soils

Geology of the project area is complex (Figure 13). The NFNR watershed above Canyon Creek is composed of a mixture of recent and older volcanic rocks, including basalt, andesite, and rhyolite. In addition, there are significant areas underlain by metamorphic rocks, including marble, schist, phyllite, and gneiss. There are igneous intrusive rocks as well, including granite, granodiorite, and quartz diorite.

Of particular note is the presence of landslides in the immediate vicinity of the project reach. The NFNR cuts through, and flows along, the Church Mountain landslide. The very large mass wasting deposit is believed to have been emplaced at about 2400 years B.P. (Tabor and Haugerud 1999). The landslide deposits occupy the valley floor from wall to wall, and along the valley axis for over 2 miles. The debris has changed the shape of the valley floor and greatly affected the river’s form and processes.

In addition, there are numerous landslides in the Canyon Creek watershed. Two large earth flows, the Jim Creek slide, and the Bald Mountain slide, are located on the upstream side of the canyon from which the creek gets its name. The two slides are directly opposite of each other, and the toes of each appear at the creek. It is believed that these slides occasionally block Canyon Creek, with subsequent catastrophic dam-break floods (Kerr Wood Leidel, 2003).

Geology of the Canyon Creek watershed is diverse (MBSNF 1995d). Meta-sedimentary rocks of the Chilliwack group dominate the upper watershed. The lower or southwest portion of the watershed contains Chuckanut sandstone, a sedimentary rock, while the middle section contains Chilliwack meta-sedimentary rock and meta-igneous material. Bedrock found in the basin has been metamorphosed in many areas to varying degrees (Jones 1984). The basin was repeatedly glaciated during the last ice age, with the most recent episode ending approximately 12,000 years ago. This glacial activity scoured the basin to bedrock and left poorly developed soils that vary from glacial till to glacial lake sediments and recessional outwash.

Soils of the project area are young; their characteristics are mostly dominated by the nature of the parent materials. A map of the soils in the vicinity of the three project section is shown in Figure 14. The recent floodplain and alluvial fan deposits are represented by gravelly loam and gravelly loamy sand. Nearby bedrock-derived soils are very gravelly loam and andic cryochrepts. Most of the valley floor is underlain by alluvium, with virtually no soil development (“river wash”).
Figure 13. Geologic map of the NFNR watershed.

Source: WDNR geology GIS layer.
Figure 14. Soils of the project area.
4.3 Geomorphology

4.3.1 North Fork Nooksack River

The NFNR emanates from the glaciers and steep, high mountains of the North Cascades. Because of the sediment supply from the glaciers, and the contributions of mass wasting events, the river and its tributaries have an ample sediment supply. In fact, the NFNR is transport-limited, and is a braided stream in the project reach. This means that there is more sediment load available that there is stream power to move it through. That is why there are multiple unstable channels that in some locations cross nearly the entire floodplain. In addition, recent timber harvest practices may have contributed to streambank instability, which in turn generates sediment and more instability (Indrebo, 2000). Total sediment load of the NFNR has been estimated at 325,000 tons/year (Westbrook, 1988). This includes both suspended sediment and bedload.

Just upstream from the project vicinity, the NFNR flows through deposits of the Church Mountain Landslide (see section 4.2). The river has incised deeply into the landslide deposits, but where it leaves the landslide deposits (immediately downstream from the Warnick Bridge), it becomes much wider. Just downstream from the project reach, a landslide from Slide Mountain, on the south, flowed and stopped in the valley floor. The river has chipped away at this slide, but it is still directing flow to right side of the floodplain (see Figure 3).

Previous work done on the NFNR has attempted to characterize stream power, in order to predict risk of erosion. WSDOT (2001) completed a study that calculated stream power by river mile. At the Canyon Creek confluence (RM 55), there is an estimated 10 percent increase in stream discharge; additionally, there is an increase in slope. As a result, there is a 250 percent increase in stream power at the confluence. This drops off rapidly, however. The next point of channel slope measurement downstream in the 2001 was 2.5 miles away.

The river reach can be divided into 3 subreaches based on planform pattern: subreach 1, which is from downstream of the bridge to just below Warnick Bluff; subreach 2, the constricted area where the bridge is located; and subreach 3, above the confluence with Canyon Creek. Figure 15 shows the reach delineations. These subreaches roughly correspond to Indrebo’s (2000) Reaches 7, 8, and 9. Subreach 1 is very wide, braided, with multiple channels. Subreach 2 is short and straight, with a single channel. Subreach 2 is controlled by the Canyon Creek Alluvial Fan on the right, and the remnants of the Church Mountain landslide on the left. Subreach 3 is braided and has multiple channels, but it not as wide as subreach 1.

Table 1 shows a comparison of key characteristics of the subreaches. The sediment sizes were determined from averaging the pebble count data for each subreach. The median particle size (D50) for subreaches 1 and 3 were very similar, while the D50 for subreach 2 was considerably smaller. The gradient of subreach 2 was considerably higher than for either of the other subreaches. With a higher gradient, one expects more stream power, and thus a coarser streambed than other, less powerful reaches. However, this is not what we found. The reason for the smaller D50 in subreach 2 could be in the way pebble count sites were sampled. Although sampled during low flow (189 cfs at Glacier), only easily accessible gravel bars were sampled (see Figure 15 for pebble count locations). The
streambed particles in the active channel are likely significantly larger. The D84 and D16 are also smaller in subreach 2 than in the other two subreaches. Figure 17 shows the cumulative percent finer sediment values for each of the pebble count sites. Prior sediment sampling of the NFNR indicates that the median sediment size increases at the confluence with Canyon Creek, relative to the confluence with the next major tributary upstream, Wells Creek (Westbrook, 1988). The D84 increases significantly at the Canyon Creek confluence, while the D16 decreases.

The constriction at subreach 2 is analogous to the apex of an alluvial fan; the area below it, which is the upper portion of subreach 1, is in some ways like an alluvial fan. As the floodplain suddenly widens, stream power drops, and sediment drops out. This is reflected in the longitudinal bars present in the river profile and plan view. With no constraints, the deposition of sediment at this location becomes stochastic, and can vary wildly with each flood, minor or major. This leads to a complex response downstream, as indicated by subsidiary lobes of sediment.

These lobes may also loosely represent bedform waves that are moving through the system. The concept of sediment waves was used to describe sediment movement in a tributary of the NFNR, Cornell Creek (DaPaul, 1994). The series of cross sections at the bridge (Figure 18) indicates a wave of sediment that moved through the reach between 1992 and 2004. A second wave of sediment may be represented by apparent aggradation between 2004 and 2006. Notably, the first wave of sediment may be related to the 1989 and 1990 debris floods from Canyon Creek. In subreach 2, there is currently a large longitudinal bar.

**Table 1. Characteristics of NFNR subreaches in the project area.**

<table>
<thead>
<tr>
<th>Subreach</th>
<th>D50 (mm)</th>
<th>D84 (mm)</th>
<th>D16 (mm)</th>
<th>Gradient</th>
<th>Max. Width* (ft)</th>
<th>Min. Width* (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56.8</td>
<td>85.2</td>
<td>17.0</td>
<td>0.0087</td>
<td>1000</td>
<td>450</td>
</tr>
<tr>
<td>2</td>
<td>28.5</td>
<td>71.0</td>
<td>11.5</td>
<td>0.0067</td>
<td>182</td>
<td>158</td>
</tr>
<tr>
<td>3</td>
<td>57.0</td>
<td>101.0</td>
<td>21.5</td>
<td>0.0098</td>
<td>740</td>
<td>240</td>
</tr>
</tbody>
</table>

*Measured from 2007 aerial photographs.

The profile for each of the subreaches is shown in Figure 18. This figure shows that the channel gradient in subreach 2 is lower than either subreach 1 or 3. Additionally, LIDAR data from 2005 was used to obtain longitudinal profiles for longer portions of the subreaches. These profiles are presented in Figure 19. Although there is considerable local variation in channel bedform, and thus gradient, the surveyed profiles are broadly consistent with the LIDAR profiles. The LIDAR profiles also show that the gradient of subreach 2 is lower than either upstream or downstream. This suggests that stream power drops off very rapidly, and more quickly than suggested in the river corridor analysis. This is likely due the rapid expansion of the floodplain downstream of the bridge, and also the 90 degree bend in the floodplain.
The alluvial fan of Wildcat Creek, located downstream of the Warnick Bridge, may play a major role in the NFNR behavior. LIDAR imagery shows a sequence of nested fans, indicating rapid expansion of the Wildcat fan into the NFNR floodplain. The current active channel appears to be deflected by this fan. In addition, a portion of the highway is threatened by bluff erosion upstream of the present project area. The River Corridor Analysis (WSDOT 2001) identified a threatened area at about MP31.3. That report speculated that backwater effects from the confluence with Canyon Creek were causing accelerated erosion of the bluff at this location. Figure 20 is taken from that report, and shows the areas deemed highly susceptible to lateral erosion from the NFNR.

Analysis of aerial photographs showed that the active channel migration area (CMA) of the NFNR has expanded and contracted over time. For the purposes of this study “Active CMA” means the width of floodplain that includes all active channels and areas free of vegetation; the active CMA width includes vegetated bars that are surrounded by active channels. Figure 21 shows the variation (with selected years) over time, beginning with 1938. The CMA in 1938 was only slightly narrower, on average, than the 2007 active CMA. The 1966 CMA was significantly wider in some areas than in 2007. Notably, this took place well before the dam break floods on Canyon Creek, and there are no signs of major disturbance on Canyon Creek. The 1982 active CMA was narrower in most of the project reach than in 2007. Although no attempt was made to tie the widening of the CMA in the mid-1960s to a specific flood event, the narrowing of the floodplain subsequent to 1966 suggests a period relatively free of disturbances. The terraces and gravels bars were stable enough to allow riparian vegetation establish and encroach on the channel. Several major disturbances (floods) occurred between 1982 and 2007, both on Canyon Creek and the NFNR. The active CMA in subreach 1 was more variable in width and location than in subreach 3. In subreach 2, the active CMA did not change in location and changed very little in width over the period of record.

The CMA analysis highlights that the system expands and contracts over time, and is affected not only by Canyon Creek inputs, but also by influences upstream (likely Glacier Creek and other major tributaries).
Figure 15. Geomorphic features of the project reach.
Figure 16. Sediment curves for subreaches 1, 2, and 3, on the NFNR.
For pebble count locations, see Figure 15.
Figure 17. Cross-sections of subreach 2 looking upstream, Warnick Bridge.
Figure 18. Surveyed longitudinal profiles (water’s edge) of the NFNR.
For locations, see Figure 15.

Figure 19. LIDAR-derived longitudinal profiles of subreaches 1, 2, and 3.
Figure 20. Segments of SR542 vulnerable to erosion (shown in red).

(WSDOT 2001)
Figure 21. Active channel migration zones in the project reach, 1938-2007.
4.3.2 Canyon Creek Alluvial Fan

The Canyon Creek alluvial fan is Holocene in age (<11,000 years old). Debris flows and floods created the alluvial fan surface of more than 220 acres (see Figure 3). The fan apex is located at about 865 feet, where the creek emerges from a canyon. The creek makes a nearly 90 degree turn to the left, flowing in the opposite direction of the NFNR for about 0.7 miles before joining the river. The fan gradient is about 2.5 percent. The low flow channel is between 15 and 25 feet wide. However, there are multiple, anabranching channels; the active channel (historic alluvial fan) ranges in width between 200 and 450 feet in width. Bedrock is exposed in the low flow channel in the lower 1/3 of the historically active fan.

Glacial scour and deposition are primarily responsible for the landforms in Canyon Creek. Glacial retreat left steep, unstable slopes, while depositing recessional gravels as terraces along the upper slopes. Where bedrock is near the surface or deposits are consolidated, water movement/infiltration can be limited or confined. The valley floor contains glacial outwash in the middle portion of the watershed. The watershed contains massive landslides. Large translational and deep seated rotational failures occurred as the over-steepened slopes adjusted to more stable angles after glacial retreat.

At the confluence with the NFNR, there is a complex relation between sediment load and gradient of both rivers. When a large flood occurs on Canyon Creek, the toe of the fan may extend into the active channel of the NFNR. However, between these events, the much greater stream power of the NFNR will erode into the toe of the fan, which in turn steepens the gradient of lower Canyon Creek. The work by Indrebo (2000) suggests that the debris from Canyon Creek (particularly from the 1989 debris flood) may act as a sediment dam; Indrebo found that the NFNR widened above the confluence with Canyon Creek, and narrowed substantially below (between 1989 and 1991).

The combined sediment loads of the NFNR and Canyon Creek create a “sediment sill” in which there is a short, very steep slope (see Figure 18). Field evidence suggests that the location of the sill varies depending on the sediment input of both streams, and the flood activity on the NFNR. The sill advances down-valley after a major flood event on Canyon Creek. The sill retreats when Canyon Creek is relatively inactive, and the NFNR flows incised into it.

4.4 Hydrology and Flow Conditions

The NFNR watershed climate is typical of the mild wet conditions of the west slopes of the Cascade Mountains (Indrebo, 2000). The mean annual precipitation in the watershed varies from approximately 60 inches in the lower basin to as much as 130 inches in the upper watershed. Roughly 75 percent of the total annual precipitation within the watershed falls between October and March, as both rain and snow. Approximately one quarter of the precipitation during that period falls as snow over the high-elevation portions of the watershed. Within mid-elevation areas, storms produced by warm fronts often cause rapid melting of the transient snow pack, which produces large runoff (“rain-on-snow”) events. Roughly 25 percent of the watershed lies between 1,500 and 4,500 feet, within which frequent rain-on-snow events occur.
The NRNR is dominated by two runoff seasons, the winter and the late summer. The winter runoff is fueled by strong Pacific fronts that bring heavy amounts of precipitation, including relatively warm storms that result in rain-on-snow events. The summer high flows are a result of snowmelt. Glaciers contribute to base flow through late summer and fall, maintaining relatively consistent flows (and higher flows than in equivalent, non-glaciated watersheds).

There is a good record of stream flows in the project area. The USGS operated a gage (12205500) just below the Warnick Bridge (below the confluence with Canyon Creek) between 1911 and 1938. Another gage was installed upstream (12205000) near the town of Glacier. Figure 22 shows the mean monthly hydrograph just below the confluence with Canyon Creek. Note that the closest active gage is near the junction with Glacier Creek, several miles upstream to the east.

Flood recurrence intervals have been calculated on both the NFNR and Canyon Creek. Tables 2 and 3 show the various flood recurrence intervals and associated discharges for NFNR and Canyon Creek, respectively. For reference, the peak discharge of the December 2007 flood was 6230, or about a 2-year event; the peak discharge of the November 2006 event was 8200 cfs. Of particular note is that the 2-year flood on the NFNR is greater than the 100-year flood on Canyon Creek. Notably, however, debris floods on Canyon Creek are considerably higher in volume than water-only floods. Whatcom County (2003) calculated the 1989 debris flood peak discharge to be 16,100 cfs; the 500-year debris flood was estimated to be 25,000 cfs.
Figure 22. Mean monthly flow on the North Fork Nooksack River.

Table 2. Recurrence flow at USGS gage 12205000 near RM 63.

<table>
<thead>
<tr>
<th>Return Period (yrs)</th>
<th>Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4770</td>
</tr>
<tr>
<td>2</td>
<td>6650</td>
</tr>
<tr>
<td>5</td>
<td>7924</td>
</tr>
<tr>
<td>10</td>
<td>8804</td>
</tr>
<tr>
<td>25</td>
<td>9948</td>
</tr>
<tr>
<td>50</td>
<td>10828</td>
</tr>
<tr>
<td>100</td>
<td>11733</td>
</tr>
</tbody>
</table>

(Whatcom County, 2007)

Table 3. Recurrence flows at Canyon Creek.

<table>
<thead>
<tr>
<th>Return Period (yrs)</th>
<th>Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2705</td>
</tr>
<tr>
<td>5</td>
<td>3555</td>
</tr>
<tr>
<td>10</td>
<td>4010</td>
</tr>
<tr>
<td>25</td>
<td>4835</td>
</tr>
<tr>
<td>50</td>
<td>5340</td>
</tr>
<tr>
<td>100</td>
<td>5970</td>
</tr>
</tbody>
</table>

(Whatcom County, 2003).

4.5 Riparian Conditions

The riparian condition of the NFNR and Canyon Creek are generally poor in the project area. There is little if any streamside vegetation, except on the margins of the active channel zone. The main channel, as well as most of the side channels, has little or no
shade. Even in the relatively narrow subreach 2, the shade provided by nearby vegetation is minimal; the banks are regularly scoured of vegetation.

4.6 Large Woody Debris

Due to the nature of braided streams, LWD does not play a key role in the subreaches of NFNR; however, wood may have been more common, and more functional, prior to European settlement. Timber harvest removed large old growth trees from the valley floor. These may have been large enough to withstand the high sediment load of the NFNR. The presence of large log jams downstream on the NFNR in the late 19th century has been documented (Collins and Sheikh, 2003).

Current habitat restoration efforts in the area (WRIA 1 committee, 2001; NMFS, 2007) may introduce more wood into the system, building engineered log jams that are specifically designed to trap additional LWD coming downstream. However, the project reach currently has very little wood that functions as aquatic habitat. Wood is routed quickly through the reach, and because the floodplain is wide, the thalweg of the NFNR is isolated from banks with wood which might be recruited.

4.7 Water Quality

Water quality is generally very good along the NFNR. The NFNR and its tributaries above Maple Creek are classified as “AA” by the Department of Ecology (1997). However, it is listed on the 303(d) list as exceeding standards for fine sediment, about 4 miles upstream from the Warnick Bridge. The river is naturally high in fine sediment during the mid- to late-summer, because flows are dominated by glacial meltwater at that time. Some fine sediment from logging activities may also contribute (WRIA 1 Planning Unit, 2001).

The principal water quality concern in the North Fork is water temperature. Although temperature is not a concern in the glacially driven flows of the mainstem North Fork, five of its tributaries are on the 303(d) list for temperature. These listings are primarily of concern for fisheries.

Additionally, Canyon Creek was listed for temperature in 1996. Temperature data collected in Canyon Creek shows that although approximately 14 percent of the July observations exceed the criterion, only about 7 percent of all of the temperature observations (July – September) exceed the criterion. Based on the entire dataset, Canyon Creek would not meet the 10 percent criterion and would not qualify for listing on the 303(d) list. There are no observations at this location that fall in the range that would cause acute temperature effects on fish. During July of 1996, however, there was a 10-day period in which temperatures during the afternoon reached the sub-lethal effects range.

4.8 Fish Utilization and Habitat Availability

The North Fork Nooksack River system supports Chinook, chum, coho, pink, steelhead, cutthroat and bull trout/Dolly Varden. Cutthroat are presumed to be present. A few sockeye have also been observed.

North Fork spring Chinook within the river system represent a distinct stock. It is a native population with composite production, and its status is considered to be critical based on
chronically low escapement. This species is currently listed as threatened under the federal Endangered Species Act (ESA).

Chum within the system are also considered a distinct stock. It is a native stock with wild production whose status is healthy. Chum tend to use primarily the lower sections of the NFNR and also spawn in some tributary streams.

Steelhead are also identified as a distinct stock; they are listed as threatened under ESA. They are of the Mainstem/NFN stock and they spawn in the Mainstem, North Fork, and tributaries. It is a native, wild stock, sustained by natural production whose status is unknown (WDFW 2009).

Two stocks of bull trout/Dolly Varden are identified as using the NFN River and/or its tributaries. These are the lower Nooksack and Canyon Creek Stocks. The stocks are native and are believed to be composed of anadromous, fluvial, and resident life history forms, which have the potential to commingle in many of the spawning areas. Bull trout/Dolly Varden are currently listed as threatened under the ESA.
5.0. Evaluation of Geomorphic Failure.

This Section discusses the causes of, and treatments for, geomorphic failure, at the three sections.

5.1 Causes and Mechanisms of Geomorphic Failure

5.1.1 Warnick Bluff

Warnick Bluff is in various states of activity along its entire length. However, almost all of it is steeper than the angle of repose of its material (about 33 degrees). This suggests that it inherently unstable, regardless of recent erosion. The materials composing the bluff are unconsolidated, and supported by the network of clasts. Furthermore, where the active channel of NFNR is close to the toe of the bluff, there is a risk of additional toe erosion and undercutting of the bluff.

A stream bank stability analysis model, B-STEM (Simon et al, 2000), was used to characterize relative risk of bluff failure, using a number of assumptions (see Appendix). We found that the factor of safety (Fs) of the 2005 bluff profile (year in which LIDAR was obtained), was only 0.44. Assuming a wedge failure mode, and a depth to groundwater of 29 feet (based on elevation of seeps observed in the field), the bluff could fail on its own at any time, retreating by about three feet. Additionally, erosion of the toe by the NFNR can remove lateral support for the bluff, increasing the size of the failure. Several floods were simulated, and that showed that the toe can erode and further destabilize the bluff.

5.1.2 Warnick Bridge

The bridge is located at a natural constriction in the NFNR floodplain, where the Canyon Creek alluvial fan lies directly across from the downstream end of the Church Mountain landslide. However, the bridge itself constricts flows during floods. The sharp spike in stream power at the Canyon Creek confluence, combined with the constriction of the bridge itself, causes a very high potential for scour. The fact that scour is not worse is likely due to the high sediment load of the NFNR, which consumes significant energy that might otherwise be directed into scour. The sediment sill, when it moves down valley, poses a high risk of scour of the bridge approaches.

5.1.3 Canyon Creek Alluvial Fan

The alluvial fan is a threat to the highway because of the nature of alluvial fans and the location of the highway. The Canyon Creek Alluvial fan is a large and very active fan, fed by a highly erodible watershed, and supplemented by the increased peak flows and sediment loads that are associated with timber harvest practices (Indrebo, 2000). Extreme events on the fan are likely caused by rapid movement of one or both of the two very large deep-seated landslides located above the alluvial fan. These result in damming of the stream following by breach of the dam with large quantities of water and sediment.

While the active width of the fan has been much the same since 1938, it has been narrowed somewhat by the construction in 1994 of the levee. The narrowing of the active fan width could have the effect of decreasing the amount of temporary storage of sediment. The result can be increased through-put of sediment.
The large debris floods of 1989 and 1990 resulted in a “slug” of sediment from Canyon Creek into the floodplain of the NFNR. The river has been reworking the sediment since. Additionally, the floods of fall 2006 and 2007 may have introduced additional sediment. There has been a migration of the active channel of the NFNR to the north, in the vicinity of Warnick Bluff, since 1938, but it appears to have accelerated since 1990.

Whatcom County (2003) commissioned a study to assess risks on the alluvial fan. Figure 23 shows the hazard zonation map developed as a result of the investigation. The modeled event is a 500-year debris flood, and is thus rare event. The highway is threatened for along the entire distance that it traverses the alluvial fan. The damage level gets higher to the east, closer to the active portion of the fan. The County is considering removing a portion of the 1994 dike. The 2003 study included two-dimension hydraulic modeling that indicated that the flow from the 500-year event would be contained within the existing channel, However, it also showed that flow velocities would exceed the existing levee’s rip rap design flows. While this indicates that highway is at risk under existing conditions, it does so only for the 500-year event. More frequent return interval floods that would otherwise be contained in the existing channel would have unpredictable flood paths if the berm were removed. This is in part because sedimentation would alter the floodplain, and new channels would develop. The logical conclusion is that, in general, removal of the levee increases the risk of the highway being affected by floods on the Canyon Creek fan.
Figure 23. Canyon Creek hazard zonation map.
Whatcom County, 2003. Based on composited scenarios of 500-year debris flood event. Orange areas indicate high flows depths (up to eight feet), high velocities (up to 12 feet per second), and direct debris impact. Yellow indicates area at risk of moderate flow depths (up to four feet) and velocities (up to six feet per second), and channel migration. Green indicates lowest risk zone, with flow depths of up to two feet and velocities of up to three feet per second.

5.2 Abating the Primary Mechanisms of Failure

5.2.1 Bluff retreat
There are two primary means of addressing the threat of bluff retreat: slope protection and highway relocation.

Various means of slope protection could be employed to reduce the risk of additional slope failure. Toe protection can serve to minimize the undercutting of the bluff by the river. Slope protection could be employed to prevent slope retreat. Such measures would include bolts, retaining walls, Shotcrete application, and benching.

Toe protection has been installed at the base of the most active section of Warnick Bluff, and more is planned farther upstream on the NFNR. However, the results of BSTEM suggest that the bluff could retreat by slope failure alone. Additionally, given the dy-
namic nature of the channel, the toe protection may not fully protect the toe of the bluff during large floods. In such an active braided system, the log structures could be buried by aggradation, leaving the base of the bluff vulnerable to undermining.

Highway relocation can also abate the slope failure by avoidance. This has already been done on a small scale, when the highway was moved 30 feet to the north in the section adjacent to the recently retreated portion of the bluff.

5.2.2 Bridge scour and erosion

Bridge scour and erosion is primarily a result of the location and configuration of the Warnick Bridge. The main method of abating these mechanisms is redesign and/or relocation of the bridge.

The constriction presented by the bridge could be removed by lengthening the free span and setting the concrete piers back. This would give the NFNR as much room as possible, minimizing the potential for backwater effects on the river and Canyon Creek.

5.2.3 Canyon Creek Alluvial Fan erosion

As with bluff retreat, there are two primary means to address the threat of erosion and sedimentation to the highway: protection and relocation.

The highway can be protected from the threat of erosion and sedimentation. Protection schemes have already been suggested in previous studies. Whatcom County (2003) first raised the possibility of the construction of a levee adjacent to the highway. Their report suggested a “deflection berm” 1000 feet long and 30 feet high, to be placed long the north side of the highway, ending at the west approach to the Warnick Bridge. The concept was furthered in the 2007 habitat restoration study commissioned by the county (Whatcom County 2007). This study outlined more specific ideas about the construction of the deflection berm, including rock size (based on the modeled depth of flows from the previous report). The study provided a preliminary design to protect the slope along the existing swale adjacent to the north side of the highway. The design included protection for the toe of the highway embankment. The toe slope protection would extend 800 feet west from the NFNR, and would be 10 to 15 feet above the existing grade. This design is intended to protect the west bridge approach and reduce the potential for highway overtopping and associated erosion.

Highway relocation can also avoid the threat of erosion and sedimentation. The 2001 North Fork River Corridor Analysis conducted by WSDOT recommended moving the highway between MP29.42 and 31.79.
6.0. Treatment Alternatives.

6.1 Alternatives Considered

The alternatives presented below are summarized in comparative fashion in Table 4.

6.1.1 No Action

Under this alternative, there would be no highway relocation, the bridge would be replaced when its structural life is complete, and there would be no advance protection from debris floods emanating from Canyon Creek.

Under the “no action” alternative, all necessary actions to protect the road embankment (excavation, placement of rock) will be addressed under emergency conditions. Any damage from potential debris or water floods would also be treated under emergency conditions. Under these conditions, habitat impacts are secondary, and may require subsequent mitigation or correction. Additionally, the highway is vulnerable in several locations along Warnick Bluff, and from the Canyon Creek alluvial fan on the other side. Continued operations will not address a long-term problem that could be catastrophic with regard to public access, and also could be very expensive to treat on an ad-hoc basis.

6.1.2 Warnick Bluff - Highway relocation MP29.7 to MP30.9

This alternative would take advantage of right-of-way (ROW) already owned by WSDOT, but not used. There is a state-owned right-of-way (ROW) located within the Glacier Springs subdivision. This ROW was purchased in the 1950s for a potential realignment that never went forward. The highway could be relocated to take advantage of the ROW. The closest point on the bluff is located 220 feet from this ROW. Figure 24 shows the location of the ROW relative to the Glacier Springs subdivision. The ROW does not extend all the way to the NFNR, however. Much of the lower portions of the Glacier Spring Subdivision would need to be acquired for new ROW.

This alternative would include sloping back of Warnick bluff in the section closest to the existing highway alignment, to a stable angle (33 degrees), and planting with native species of plants selected for root strength and site-specific characteristics.

This alternative could be combined with replacing the bridge (see section 6.1.4) at a location just to the north of the existing bridge. The route leading up to the bridge would thus be slightly to the north of the existing ROW, as indicated in Figure 25.

6.1.3 Warnick Bluff - Toe and slope protection

Under this alternative, additional toe protection could be given to the base of Warnick Bluff. The highway would not be relocated. This could consist of engineering log jams, acting as groins, or rock groins. However, potential aggradation, as part of the shifting of the active, could render any toe protection method ineffective.

A variety of slope protection measures would be employed. Retaining walls would be built, along with slope drainage measures, to stabilize the face of the bluff. Soil nails or other retaining systems might be used. However, the amount of slope protection would be likely be limited to the recently active bluff erosion sites. Slope protection for all 6000 feet of Warnick Bluff would be very difficult and expensive to undertake.
6.1.4 Warnick Bridge – New bridge with longer clear span

This alternative, which would address the potential scour problems at the east and west approaches of the Warnick Bridge, would involve constructing a new bridge adjacent to and to the north of the existing bridge. The span would need to be longer, such that the piers would not constrict the river during floods. A span of 200 feet or more would be needed, to have minimal impact on flood elevations. This would need to be a clear span bridge, which would mean that 200-foot pre-stressed steel girders would need to be hauled up SR542. Such an operation could be very difficult due to sharp curves in the highway.

6.1.5 Canyon Creek Alluvial Fan - protect west approach to Warnick Bridge

As discussed in section 5.2.3, a deflection berm along highway 542 would provide protection from potential debris floods emanating from the Canyon Creek alluvial fan. Whatcom County (2007) included in its habitat restoration plan a section on toe-slope protection. This section describes an 800-foot long deflection berm adjacent to SR542. Riprap from the section of the Canyon Creek levee proposed to be removed would be used in the deflection berm. Based on the flow depth and velocity, a range in rip rap sizes of between 3.1 and 4.2 feet would be needed. This would likely be needed only on the lower 2/3 of the height of the berm, followed by a finer rip rap above. The base of the berm would be 20 feet below current grade, to account for maximum potential scour. The crest of the berm would have a slope of three percent. This berm would have an outer face slope of 2:1 (50 percent).

Notably, this alternative would not protect the other portions of the highway that cross the Canyon Creek alluvial fan (see Figure 23).

6.1.6 Highway relocation MP29.7 to MP31.9

One potential solution to the problems at each of the three sections is to move the highway to the north. This alternative was suggested in the River Corridor Analysis (WSDOT 2001). This route was also recommended by Ecology during shoreline permit proceedings for Whatcom County’s Canyon Creek treatments: “the only long-term solution is to relocate all occupants of the alluvial fan and to re-route the Mount Baker Highway to the fan apex of Canyon Creek” (letter dated January 24, 2001 from Barry Wegner (DOE) to Whatcom County Planning and Development Services).

This alternative would involve two new bridges, one across the NFNR, and one across Canyon Creek at the apex of the alluvial fan. The bridges would need to be sufficiently long to avoid floodplain constriction that is currently a problem at the Warnick Bridge. The bridge across the NFNR would be approximately 200 feet in length, with the approach footing in the top of the banks on either side. As with replacing the bridge at the existing site, it could be very difficult to get the steel girders in place, due to sharp curves in the highway to the west. The bridge across Canyon Creek would be a 150-foot clear span bridge, using pre-stressed steel girders.

The route would cross the river at about RM 55.5; the abutment on the left bank would be built into remnants of the Church Mountain landslide. The abutment on the right bank would be built into bedrock. The route would follow the base of the valley sidewall, stay-
ing out of the erosion hazard zone delineated in the River Corridor Analysis (WSDOT 2001). The bridge across Canyon Creek would be constructed near the apex, upstream from the alluvial fan. The bankfull width of the creek at this point is about 60 feet; the bridge span would be about 150 feet, so that the piers for the bridge span would be built in the top of the adjacent terraces, and would not be affected by debris flows coming down Canyon Creek.

This alternative would not only avoid the problems at Warnick Bluff, Warnick Bridge, and the alluvial fan, it would also avoid the section of highway threatened by the NFNR at MP 31.3. Under this alternative, the new route could be built while the old route and bridge continue to be used, thus minimizing traffic disruption.

This route may have some design issues. The land surface along some portions of the route approach 10%. Also, the approach to NFNR has a steep hill just before dropping down to the river. The standard maximum road grade for the Northwest Region is 6%. Therefore construction would involve substantial cuts and fills, depending on the final location of the alignment.

There are no substantial areas of unstable slopes along the route, according to both the Whatcom County GIS (Whatcom County website, 2008) unstable slopes and landslides layers, and the Washington Department of Natural Resources slope stability layer (WA DNR, 2008). Also, based on review of aerial photographs, snow avalanche hazard appears to be minimal, as there are no avalanche chutes on this site of the valley.

By crossing the apex of the alluvial fan, this route would avoid nearly the entire hazard zone of the fan (Whatcom County, 2003). This route crosses older deposits of the Canyon Creek alluvial fan, portions of the Church Mountain landslide

6.2 Preferred Alternative – Multi-phase Approach

A phased approach is the best long-term solution, since it avoids a number of issues along the river corridor in this reach. This alternative incorporates the alternatives described in sections 6.1.2, 6.1.5, and 6.1.6. The first phase would consist of relocating the highway farther north of Warnick Bluff, using the unused WSDOT right-of-way (see Section 6.1.2). The second phase would consist of providing protection for the west approach (as in Section 6.1.5). In addition, riprap protection of the piers 1 and 2 would be rebuilt or replaced. The existing bridge would be retained in the short term. The third phase would be much farther into the future, and would involve moving the highway even farther north, to the route described in Section 6.1.6.

This alternative would avoid flooding, erosion, and deposition from Canyon Creek, and would avoid scour and erosion of the approaches to the Warnick Bridge. Additionally, the highway would not be affected by bluff retreat, as it would be far removed from Warnick Bluff (see Figure 23).

Although this is the most costly alternative in terms of capital investments, it will protect the highway from long-term risks, which would cost more to fix when done as multiple emergency repairs. The initial phases of the alternative would provide adequate protection for the short term, during which planning and funding for the long-term phase could be pursued. Consideration of each of the project sections separately would likely favor less expensive solutions, specific to each. However, taken collectively, the consideration
of the reach as a whole indicates that a broader, long-term solution of highway relocation is warranted. Additional studies, such as a risk-benefit analysis, could be conducted to define a long-range schedule of project implementation.
### Table 4. Alternatives Evaluation Matrix.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Applicable Location</th>
<th>Description</th>
<th>Advantages</th>
<th>Risks</th>
<th>Habitat Effects</th>
<th>Relative Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Action</td>
<td>All locations</td>
<td>Highway configuration remains the same; existing maintenance practices continue; mitigation required</td>
<td>No permitting</td>
<td>Continued maintenance activity; potential for expensive emergency fixes</td>
<td>Minimal</td>
<td>Low (short term); High potential (long term)</td>
</tr>
<tr>
<td><strong>Toe and Slope Protection</strong></td>
<td>Warnick Bluff Section</td>
<td>Install protection measures at toe and face of Warnick Bluff</td>
<td>Permitting relatively easy.</td>
<td>Aggradation could render toe protection ineffective; could be difficult to construct</td>
<td>Minimal</td>
<td>Moderate</td>
</tr>
<tr>
<td>Highway re-location MP 29.7 to MP30.9</td>
<td>Warnick Bluff Section</td>
<td>Move highway to the north onto existing ROW</td>
<td>Moves highway from bluff erosion area; can slope back bluff to stable angle; uses existing ROW for a portion of new route.</td>
<td>Sections of highway still could be subjected flooding, deposition, and erosion from Canyon Creek alluvial fan</td>
<td>Minimal</td>
<td>Moderate/high</td>
</tr>
<tr>
<td>New bridge with longer span</td>
<td>Warnick Bridge Section</td>
<td>Construct new, longer bridge to the north of existing bridge</td>
<td>Removes constriction of floods; can keep highway open during construction.</td>
<td>Sections of highway still could be subjected flooding, deposition, and erosion from Canyon Creek alluvial fan</td>
<td>Portion of riparian zone destroyed where new bridge built; habitat at old bridge site could be restored</td>
<td>Moderate</td>
</tr>
<tr>
<td>Protect western approach to Warnick Bridge</td>
<td>Canyon Creek Alluvial Fan/Warnick Bridge</td>
<td>Construct deflection berm adjacent to west approach to Warnick Bridge</td>
<td>Protects most of high hazard portion of alluvial fan; easy to permit and build.</td>
<td>Sections of highway still could be subjected flooding, deposition, and erosion from Canyon Creek alluvial fan</td>
<td>Portion of riparian zone destroyed where berm is constructed</td>
<td>Low-moderate</td>
</tr>
<tr>
<td>Highway re-location MP29.7 to 31.9</td>
<td>All locations</td>
<td>Relocate highway north of this section of the NFNR, across apex of Canyon Creek alluvial fan. Includes two new bridges. Most of existing alignment kept open.</td>
<td>Removes highway from alluvial fan completely; removes risk of bluff erosion; avoids problems cause by constriction in subreach2; avoids potential effects of erosion at MP31.4</td>
<td>Long time to construction; complicated permitting, land acquisition processes; possible geotechnical difficulties/costs; maintenance costs for legacy ROW. Increases highway length.</td>
<td>Some riparian habitat lost at Canyon Creek crossing; minimal at new NFNR crossing</td>
<td>Very High</td>
</tr>
<tr>
<td>Multi-phase Approach</td>
<td>All locations</td>
<td>Initial re-location through Glacier Springs; Warnick Bridge west approach protection; long-term phase of moving highway to apex of Canyon Creek Fan.</td>
<td>Avoids most short- and long-term threats to the highway.</td>
<td>Long time to construction; complicated permitting, land acquisition processes; possible geotechnical difficulties/costs; maintenance costs for legacy ROW. Increases length of highway.</td>
<td>Some riparian habitat lost at Canyon Creek crossings; minimal loss at new NFNR crossing</td>
<td>Very High</td>
</tr>
</tbody>
</table>
Figure 24. Potential highway relocation routes.
7.0 Conclusions

The area addressed in this report is a collection of sites that are related by geomorphic processes. The interaction of these processes is complex and complete description and analysis of these processes is beyond the scope of this document. However, enough information was obtained through analysis of photographs, topography, flood history, and sedimentation to make recommendations to protect the highway.

The steep profile of Warnick Bluff is a result of periodic lateral erosion by the NFNR. The NFNR has migrated to right sides of the floodplain, undermining the deposits of the Canyon Creek alluvial fan (and perhaps old river deposits), and inducing slope failure. The bluff retreat at MP 29.8 is the first location to immediately threaten the highway. However, a railroad and its right of way have already been lost due to river erosion and subsequent bluff retreat. The highway is still threatened, even though a portion was relocated in 2006. There is a long term threat of bluff retreat along the entire 6000-foot length of Warnick Bluff. Due to the stochastic nature of the NFNR braided reach, erosion could accelerate at any point of the rest of Warnick Bluff.

The Warnick Bridge has experienced relatively minor erosion of the east and west approaches. However, rip rap that has been installed to protect the piers has been undermined and has partially collapsed into the river. Additionally, the bridge constricts flood flows in a way that likely causes instability downstream and possibly upstream.

The Canyon Creek alluvial fan poses threats to the highway. The risk of damage is greatest near the west approach to Warnick Bridge. However the entire section of highway between Warnick Bluff and Warnick Bridge is threatened by flooding, erosion, and deposition on the Canyon Creek alluvial fan. Future habitat restoration efforts may increase the risk of highway damage.

A phased program of highway relocation and protection is recommended. Treatments for each of the individual sites were examined, but consideration of the sites, as whole, points to a broader solution. The first phase would involve moving the highway between MP 29.7 and MP 30.9, partly locating the route on an unused WSDOT right-of-way. This would be followed by replacement of the Warnick Bridge and protection of the western approach using a rock berm. Long-term planning would be conducted with the goal of eventually moving the highway route completely out of harm’s way, between MP 29.7 and MP 31.9. This alternative addresses both the immediate threats to the highway and the long-term risks present in this reach of the NFNR.
8.0. References.
War Department, 1915, topographic map of Van Zandt Quadrangle, scale 1:63,000.
Appendix. B-STEM worksheets
### Input bank materials

Specify the erodibility of the different materials. Use the drop down boxes to select material type or select "Enter own data" and add values in the 'Bank Model Data' worksheet. If you select a material, the values shown in the 'Toe Model Data' worksheet will be used. Once you are satisfied that you have completed all necessary inputs, hit the "Run Shear Stress Macro" button (Center Right of this page).

<table>
<thead>
<tr>
<th>Bank Material</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
<th>Bank Toe Material</th>
<th>Bed Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.09</td>
<td>62.21</td>
<td>19.44</td>
<td>0.71</td>
<td>Enter own data</td>
<td>Gravel (20 mm)</td>
<td>Fixed bed</td>
</tr>
<tr>
<td></td>
<td>0.925</td>
<td>0.019</td>
<td>0.029</td>
<td>0.119</td>
<td>Enter own data</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Erodibility Coefficient used (cm³/Na)**

**Estimate critical shear stress τc**

<table>
<thead>
<tr>
<th>Bank Protection</th>
<th>No protection</th>
<th>Input bank protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bank Toe Protection</td>
<td>No protection</td>
<td>Input toe protection</td>
</tr>
</tbody>
</table>

- Average applied boundary shear stress: #DIV/0! Pa
- Maximum Lateral Retreat: 0.00 cm
- Mean Eroded Area - Bank: 0.00 m²
- Mean Eroded Area - Bank Toe: 0.00 m²
- Mean Eroded Area - Bed: 0.00 m²
- Mean Eroded Area - Total: 0.00 m²

---

**Export Coordinates back into model**
### Erodibility Data

These data are used when selecting the different material types. Note that changing the values here will change the values in the drop down boxes of the Toe Erosion Model.

<table>
<thead>
<tr>
<th>Bank Material</th>
<th>Diameter (m)</th>
<th>K (cm²/Na)</th>
<th>Bank Toe Material</th>
<th>Diameter (m)</th>
<th>K (cm²/Na)</th>
<th>Bed Material</th>
<th>Diameter (m)</th>
<th>K (cm²/Na)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulders (256 mm)</td>
<td>0.256</td>
<td>248.83</td>
<td>0.006</td>
<td>Boulders (256 mm)</td>
<td>0.256</td>
<td>248.83</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>Cobble (64 mm)</td>
<td>0.064</td>
<td>62.21</td>
<td>0.013</td>
<td>Cobble (64 mm)</td>
<td>0.064</td>
<td>62.21</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>Gravel (20 mm)</td>
<td>0.02</td>
<td>19.44</td>
<td>0.023</td>
<td>Gravel (20 mm)</td>
<td>0.02</td>
<td>19.44</td>
<td>0.023</td>
<td></td>
</tr>
<tr>
<td>Coarse sand (1 mm)</td>
<td>0.001</td>
<td>0.71</td>
<td>0.118</td>
<td>Coarse sand (1 mm)</td>
<td>0.001</td>
<td>0.71</td>
<td>0.118</td>
<td></td>
</tr>
<tr>
<td>Fine sand (0.125 mm)</td>
<td>0.000125</td>
<td>0.09</td>
<td>0.335</td>
<td>Fine sand (0.125 mm)</td>
<td>0.000125</td>
<td>0.09</td>
<td>0.335</td>
<td></td>
</tr>
<tr>
<td>Resistant cohesive</td>
<td>-</td>
<td>50.00</td>
<td>0.014</td>
<td>Resistant cohesive</td>
<td>-</td>
<td>50.00</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>Moderate cohesive</td>
<td>-</td>
<td>5.00</td>
<td>0.045</td>
<td>Moderate cohesive</td>
<td>-</td>
<td>5.00</td>
<td>0.045</td>
<td></td>
</tr>
<tr>
<td>Erodible cohesive</td>
<td>-</td>
<td>0.10</td>
<td>0.316</td>
<td>Erodible cohesive</td>
<td>-</td>
<td>0.10</td>
<td>0.316</td>
<td></td>
</tr>
</tbody>
</table>

Enter own data

<table>
<thead>
<tr>
<th>Enter own data layer 1</th>
<th>Enter own data layer 2</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
</tbody>
</table>

9

Enter own data layer 3

Enter own data layer 4

Enter own data layer 5

<table>
<thead>
<tr>
<th>Bank protection</th>
<th>Permissible shear stress</th>
<th>Toe protection</th>
<th>Permissible shear stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>No protection</td>
<td>-</td>
<td>No protection</td>
<td>-</td>
</tr>
<tr>
<td>Plant cuttings</td>
<td>100</td>
<td>Plant cuttings</td>
<td>100</td>
</tr>
<tr>
<td>Large Woody Debris</td>
<td>150</td>
<td>Large Woody Debris</td>
<td>150</td>
</tr>
<tr>
<td>Rip Rap</td>
<td>150</td>
<td>Rip Rap</td>
<td>150</td>
</tr>
<tr>
<td>Jute net</td>
<td>22</td>
<td>Jute net</td>
<td>22</td>
</tr>
<tr>
<td>Coir fiber</td>
<td>108</td>
<td>Coir fiber</td>
<td>108</td>
</tr>
<tr>
<td>Geotextile (synthetic)</td>
<td>144</td>
<td>Geotextile (synthetic)</td>
<td>144</td>
</tr>
<tr>
<td>Live fascine</td>
<td>100</td>
<td>Live fascine</td>
<td>100</td>
</tr>
</tbody>
</table>

Need to know the critical shear stress (τc)?

<table>
<thead>
<tr>
<th>Input non-cohesive particle diameter (mm)</th>
<th>1.00</th>
</tr>
</thead>
</table>

Need to know the erodibility coefficient (k)?

<table>
<thead>
<tr>
<th>Critical Shear Stress τc (Pa)</th>
<th>0.71</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erodibility Coefficient (cm²/Na)</td>
<td>0.119</td>
</tr>
</tbody>
</table>